UCRL- 92595
PREPRINT

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This paper was prepared for submittal to 11th
Symposium on Fusion Engineering
Austin, Texas
November 18-22, 1985

October 2, 1985

Lawrence Livermore National Laboratory

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Abstract

The production of the proper magnetic field profile is fundamental to plasma confinement in magnetic mirror systems. The knowledge of this profile is important for the control of a variety of physical processes which affect particle confinement, including thermal barrier and potential well formation.

A system of probes using the nuclear magnetic resonance of protons in magnetic fields is used to measure the field strengths at various points in the Mirror Fusion Test Facility (MFTF-B). The system operates at high fields (1-12 T) with significant non-uniformity ($\lesssim$ 1.5 T/m) by taking advantage of the phenomenon of spin echo. In addition, the probes can operate in the MFTF-B environment where low temperature capability and remote operation is necessary.

These probes have been tested with laboratory magnets to develop an engineering model which relates probe signal-to-noise (S/N) ratio to probe parameters and magnetic field strengths and gradients. Engineering design formula and techniques will be presented as well as data from laboratory test stands.

"Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48."

Introduction

The success of the MFTF-B experiment is largely dependent on the proper alignment, positioning, and full current operation of the superconducting magnet set. In particular, an accurate knowledge of the magnetic field profile is necessary to achieve the desired plasma density, temperature, and potential profiles. Our goal is to build a diagnostic which can accurately measure steady-state $|B|$ to < ±2 percent at various points along the machine axis in the simplest, most direct, and inexpensive way possible. This diagnostic will be used as a one-time measurement during the magnet acceptance tests to calibrate the magnet set by determining the B-field profile as a function of magnet-coil current and position. The diagnostic will be removed before any plasma shots are made.

A set of 15 probes based on the nuclear magnetic resonance (NMR) of protons has been chosen for this diagnostic. NMR probes exploit the fact that the frequency of precession of a proton magnetic moment is proportional to the magnitude of the ambient field (4.25759 kHz/Gauss). This technique was chosen over a standard Hall probe due to increased accuracy, simplicity in construction, and insensitivity to alignment relative to the field lines.

Before discussing the actual probe design, it is necessary to establish the range of B-field magnitudes and field gradients in which the probes must operate. The probes are located at the peaks and valleys of the field profile as shown in Fig. 1 for the "choke mode" configuration of machine operation. Radially, the probes must be located outside of the 20 cm flux bundle to keep clear a path for a related e-beam magnet alignment diagnostic [1]. Thus, the 45 cm flux tube was chosen as the nominal radial location. The B-field magnitudes and field gradients for each probe location were obtained from a computer model of the MFTF-B magnet set and are listed in Table 1.

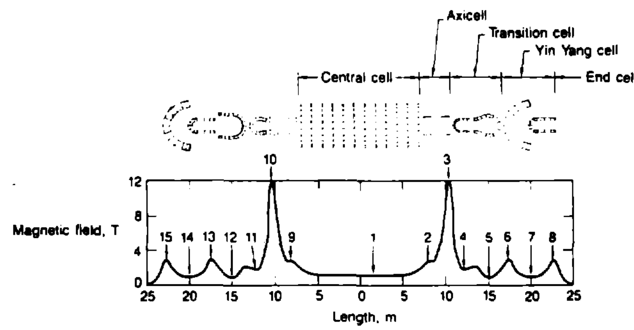

Figure 1. NMR probe locations.

Table 1

Detector	$\lvert B\rvert$ (kG)	F (MHz)	$\lvert\nabla B\rvert$ (kG/m)
1	10.5	44.7	1
2,9	23.2	98.8	3
3,10	120.0	510.9	14
4,11	16.7	71.1	2
5,12	9.6	41.0	3
6,13	30.6	130.3	3
7,14	10.1	43.0	1
8,15	30.6	130.3	3

NMR Probe Theory and Design

In its simplest form, an NMR probe consists of a small sample of proton-rich material located within the coil of a resonant circuit tuned roughly to the resonance frequency expected at the field location of interest. There are many techniques for locating the resonance frequency, including resonant absorption, decay following a pulse, and a phenomena know as "spin-echo." Although there are tradeoffs associated with each of the above techniques, our primary concern is the ability to achieve good S/N in the rather large field gradients listed above. When placed in a large field gradient, the B-field can change considerably across the material used as the sample. In general, this causes a reduction in accuracy and S/N. The spin-echo technique allows one to measure fields in regions of large gradients and, indeed, a field gradient is necessary for the spin-echo signal to exist at all. For this reason the spin-echo technique was chosen.

The theory of spin-echoes is quite involved and is discussed in depth in Refs. 2 and 3. A basic understanding can be obtained from the following brief description, along with the illustration in Fig. 2. The NMR probe is placed in the magnetic field such that the coil axis is perpendicular to the field lines. A resonant RF pulse is applied whose duration is long enough to rotate the magnetic moment by 90°. As the protons spin in this 90° plane, they will begin to separate in phase due to inhomogeneities in the field. After a time τ, a second pulse, twice as long as the first, is applied which flips the magnetic moments by 180°. The phase distribution is now also flipped so that those protons which previously lagged in phase now lead. After a time τ following the 180° pulse, all the magnetic moments in the sample will once again be in phase, producing an induced EMF in the coil. This signal is called the spin-echo and occurs only at the resonance frequency. As the field gradients become larger, the spreading in phase occurs faster, and one can use shorter, more intense, pulses to maintain a good signal.

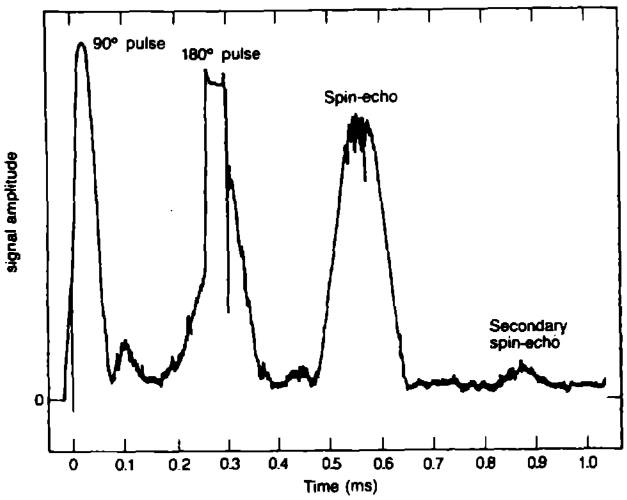

Figure 2. Typical NMR probe trace illustrating spin-echo signal (f = 96.9 MHz, B = 28.8 kG).

A number of different materials rich in hydrogen have been used by researchers for NMR samples, including water, paraffin, mineral oil, and rubber. Due to the vacuum/cryogenic environment in MFTF-B, rubber samples were chosen. Various types of rubber materials were tested, and it was found that natural rubber produced the largest signal.

A tapped resonant circuit is used to excite the sample as shown in Fig. 3 [4-6]. This circuit configuration allows the freedom to choose the impedance and bandwidth independently. The resonant frequency of the circuit is

$$f = \frac{1}{2\pi\sqrt{LC_s}} \quad , \tag{1}$$

where C_s is the series combination of C_1 and C_2. This frequency is set to equal the expected proton resonance frequency given by

$$f\ (\mathrm{MHz}) = 4.25759 \times B\ (\mathrm{kG}) \quad . \tag{2}$$

The resistor R in parallel with L is used to increase the bandwidth of the circuit so that a larger range of field values can be measured. Typically, R is adjusted for a Q of 10. The impedance is controlled

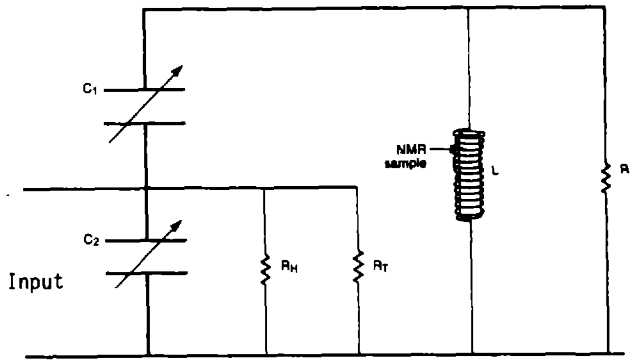

Figure 3. Tapped resonant circuit.

by adjusting the ratio of C_1 and C_2. At resonance, the input impedance is purely resistive and is given by

$$Z_{in} = R\ C_1^2/(C_1 + C_2)^2 \quad . \tag{3}$$

For coils of the size typically used for NMR probes, the inductance is given fairly accurately by the formula (MKS units)

$$L = n^2\mu_o A/(\ell + 0.9r) \quad , \tag{4}$$

where n = # turns, A = coil area, l = coil length, and r = coil radius.

R_H is a 1 kΩ, 1/4 W resistor and R_T is a small thermistor. These components are used in parallel to heat the rubber sample and monitor its temperature. This is necessary because the probes are mounted directly to the magnet LN liners. Although the sample magnetization actually increases at lower temperature [2,4], the relaxation time of the magnetic moments becomes long, requiring a pulse repetition rate which is too slow for practical observation on an oscilloscope. Therefore, the probes are kept near room temperature by passing dc current through the small resistor R_H which is in thermal contact with the NMR sample. The parallel resistance of R_H and R_T is always greater than 500 Ω, so these components have little effect on the 50 Ω ac resonant circuit.

In order to see how the S/N scales with the above circuit parameters, we need an expression for the induced signal. The EMF induced by a rotating magnetic moment is given by [4]

$$\delta\varepsilon = \omega(B_1/i)\ MV \quad . \tag{5}$$

Where ω is the resonant frequency, B_1/i is the average induced field per unit current in the coil at the sample location (center of coil), M is the sample magnetization, and V is the sample volume. The induced field per unit current is related to the inductance by

$$B_1/i = L/nA \quad . \tag{6}$$

Combining Eqs. 4, 5, and 6 gives

$$\delta\varepsilon = \omega n\mu_o MV/(\ell + r) \quad . \tag{7}$$

Since both ω and M are proportional to B, the signal scales according to

$$\delta\varepsilon \propto B^2\, n\, r^2\, \ell/(r + \ell) \quad . \tag{8}$$

To calculate the S/N ratio, an expression for the noise due to thermal motions in the NMR coil is needed. Given a small but finite effective coil resistance R_c, the thermal noise produced is

$$V_n = \sqrt{KT\Delta f R_c} \quad . \tag{9}$$

Where K is Boltzmann's constant, T = temperature and Δf is the receiver bandwidth. Since the Q of the circuit is easily measured, it makes sense to write the noise voltage above in terms of Q by substituting $R_c = \omega L/Q$, giving

$$V_n = \sqrt{KT\Delta f \omega L/Q} \quad . \tag{10}$$

In our system, Q is held constant and the quantity ωL is roughly constant for all the probe locations. So, to first order, the noise is constant and the S/N ratio is simply proportional to Eq. (8) above.

To maximize the signal given in Eq. (8) for a given field, the number of turns and probe volume should be as large as possible. However, there are two additional factors which limit the probe size. First, the coil inductance must be kept below a certain value such that resonance can still be reached with reasonable capacitors > 10 pf (≈ distributed capacitance). This limits the number of turns and hence the probe volume.

A second factor which limits the probe volume is the field gradient. The probe volume which can be excited is limited by the bandwidth of the system

$$\delta\ell = \delta B/\nabla B \propto \delta f/\nabla B \quad . \tag{11}$$

Given the excitation bandwidth, which is ~ 1/pulsewidth, one can calculate the above scale length for the typical probe dimension.

The 90° pulsewidth can be calculated using Eq. (2)

$$\tau = T/4 = \frac{1}{4B_1(G) \times 4258} \text{ sec} \tag{12}$$

where B_1 is the B-field induced in the coil by the transmitted pulse. This can be estimated by knowing the resonant circuit parameters and transmitted pulse power. Typically, for transmitted power of about 1 watt, the 90° pulse width is ≈ 20 µs.

Using the above formulas for guidance, the probes were designed for each field location with the parameters listed in Table 2. All coils were wound with 0.55 mm diameter enameled copper wire about a pure rubber core. The coil radius is 1.87 mm for all probes, except 3 and 10 whose radius is 1.13 mm. Small variable capacitors were added in parallel with C_1 and C_2 so that each circuit could be fine adjusted to obtain an input impedance of 50 Ω and a Q of ten.

System Electronics Design

A block diagram of the electronics required to operate the NMR probes is shown in Fig. 4. A variable frequency RF signal is generated by the spectrum analyzer/tracking oscillator combination. This signal is then gated to provide the 90° and 180° pulses. The pulse sequence is repeated at about 30 Hz. This pulse sequence is amplified to about 1 watt and transmitted to the probe. The spin-echo signal is returned to the spectrum analyzer after passing through a power splitter and low-noise amplifier. The spectrum analyzer acts as the receiver and allows control over the received signal bandwidth. The spin-echo pulse can then easily be observed on the oscilloscope. For very low signals, the boxcar integrator is used to time average the spin-echo signal over many repetitions. This allows the spin-echo amplitude to be plotted as a function of frequency, providing a more automated measurement and increased S/N.

The receiving electronics must be placed quite far from the NMR probes due to the strong magnetic field near the MFTF-B vessel. The resulting long cable lengths (large attenuation) and enormous ground loops are unacceptable with such small signals. Thus, an isolation transformer has been placed at the vessel port to separate the vessel ground from the receiving electronics. Also, note that large RG213 cables have been used for minimum attenuation. Internal to the vessel, a teflon coaxial cable (RG400) has been used for its good low temperature and vacuum characteristics.

Prototype Tests

Due to the uncertainties of operating in the MFTF-B environment of high B-fields, high vacuum, cryogenic temperatures, and large field gradients, we relied heavily on extensive prototype testing. Since the probe construction is relatively simple, it was possible to build a large number of probes and carefully study the effect of various probe parameters on the S/N. These results are then compared with the simple relations presented above.

A small superconducting magnet coil with a field range of 0 to 32 kG was used throughout the tests. By moving the probes along the axis of the magnet bore, a wide variety of field magnitudes and gradients could be obtained.

The received signal trace vs time for a typical probe at resonance in a 22.8 kG field (96.9 MHz) was shown above in Fig. 2. Although a boxcar integrator was used to enhance the S/N in Fig. 2, in general when the frequency, pulsewidths, and pulse height are properly tuned, S/N ratios of 20-30 dB are observed without the boxcar. All the data in Figs. 5-9 was taken without the boxcar integrator.

Table 2

PROBE #	B(kG)	F(MHz)	# TURNS	L(nH)	C1(pF)	C2(pF)	R
1	10.5	44.7	18	385	40	197	1800
2,9	23.2	98.8	8	145	22	98	1500
3,10	120.0	510.9	2	9	15	33	510
4,11	16.7	71.1	12	240	25	126	1800
5,12	9.6	41.0	18	385	48	221	1600
6,13	30.6	130.3	6	100	19	77	1300
7,14	10.1	43.0	18	385	43	212	1800
8,15	30.6	130.3	6	100	19	77	1300

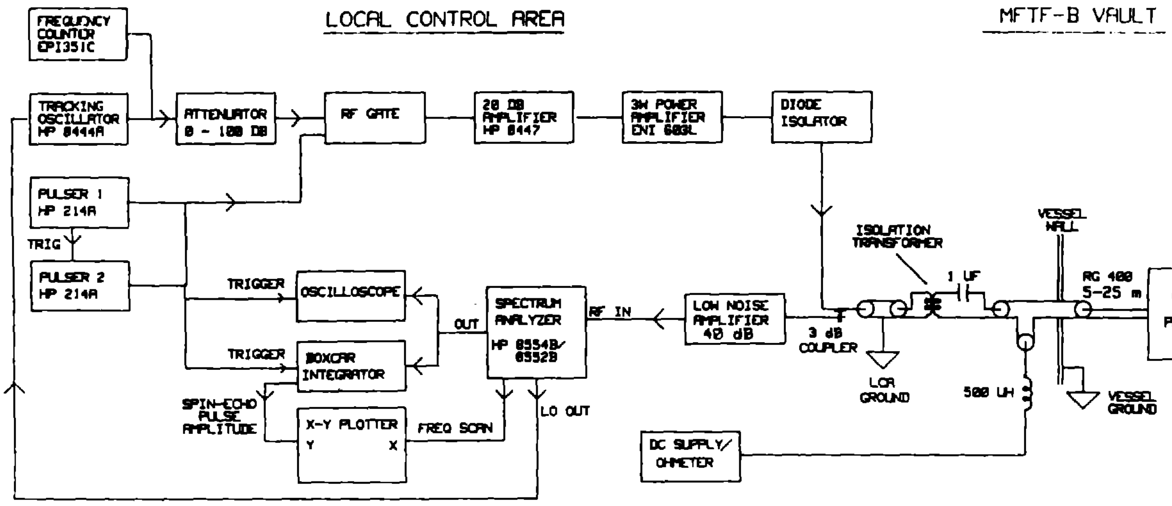

Figure 4. NMR electrical layout.

In regions of low field gradient, the 3 dB bandwidth of the spin-echo peak in Fig. 2 is about ±10 kHz, giving a magnetic field measurement resolution of better than 0.01 MHz/44 MHz = 0.02 percent. Given this accuracy, the NMR probe was used to calibrate the superconducting coil by measuring the slope of B vs magnet coil current. Both the NMR data and data from an uncorrected Hall probe are shown in Fig. 5. Note the accuracy of the NMR data compared with the Hall probe.

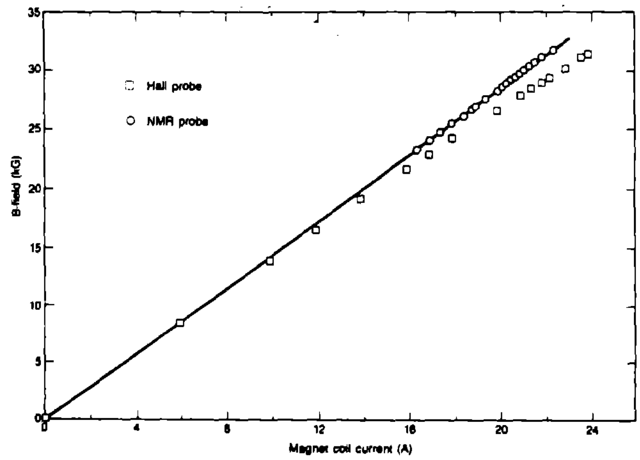

Figure 5. Comparison of NMR probe and Hall probe in calibrating superconducting test coil.

The range of magnetic fields which can be measured by a single NMR probe is limited by the bandwidth, or Q, of the resonant circuit. Each probe has been designed for a Q = 10. The S/N ratio for a probe tuned to 28.5 kG is plotted vs magnetic field in Fig. 6. The range of field values which can be measured with S/N > 1 is about ±20 percent. This is more than adequate to cover the field variations expected in MFTF-B.

As observed in Eq. (11) above, the probe volume which can be excited is limited by the steepness of the field gradient. Plotted in Fig. 7 is the S/N vs field gradient, taken at a field magnitude of 12.7 kG. With large field gradients > 5 kG/m, the S/N varies linearly with $1/\nabla B$ as expected from Eq. (11). S/N > 1 has been obtained in field gradients up to 150 kG/m. In smaller field gradients < 5 kG/m, the S/N is constant because the entire probe volume is being excited. The field gradients given in Table 1 for

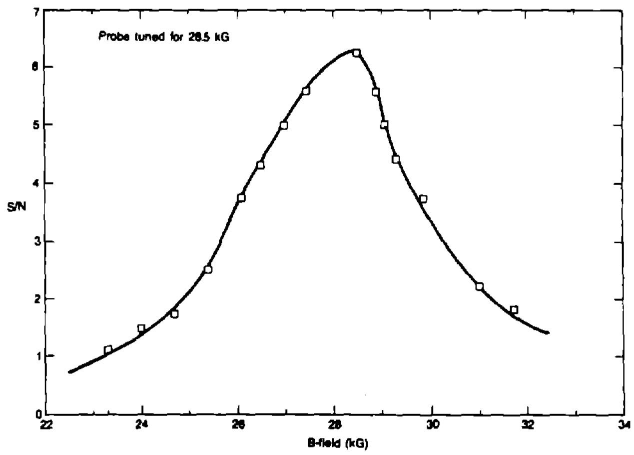

Figure 6. B-field range of a single NMR probe.

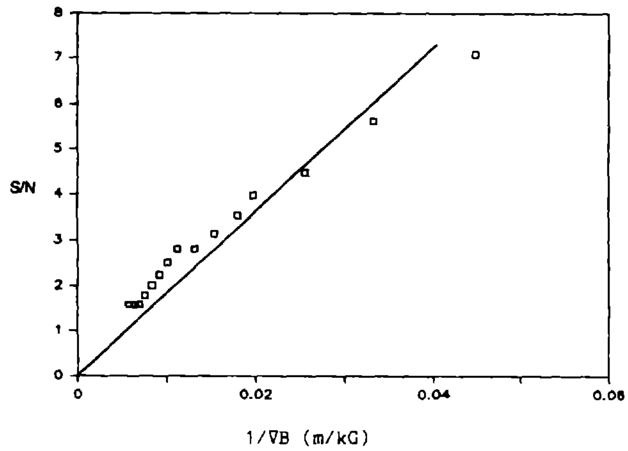

Figure 7. S/N vs B-field gradient with $|B|$ = 12.7 kG.

probe locations in MFTF-B range from 1-14 kG/m and will not significantly reduce the S/N.

If necessary, it is possible to increase the S/N in a field gradient by using a narrower pulsewidth to increase the excitation bandwidth. This is illustrated in Fig. 8 where the probe is placed in a field gradient of 50 kG/m and a field magnitude of 12.7 kG. The S/N is proportional to δf as expected from Eq. (11). The excitation bandwidth which can be obtained in this manner is often limited by the power delivered to the probe since as the pulse width is shortened the pulse height must be increased. In our system, the power is limited to a couple watts.

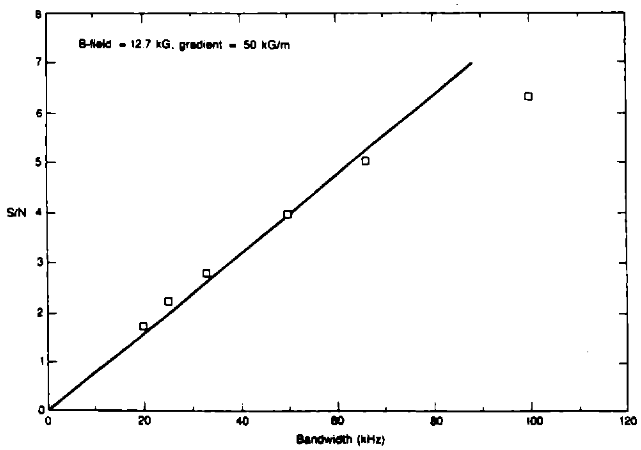

Figure 8. Variation of S/N with excitation bandwidth (δf - 1/pulsewidth).

The scaling of S/N with the B-field magnitude is a difficult measurement to make. Ideally, one would like to hold all parameters in Eq. (8) constant while varying the B-field. Unfortunately, the probe is only tuned to one field value and, as shown in Fig. 6, the S/N drops off on either side of the center frequency. To overcome this, variable capacitors were added to the resonant circuit which allowed a tuning range of about ±35 percent using a single NMR coil. The S/N of this probe is plotted vs B in Fig. 9, where the probe is retuned for each data point. Although the data range is limited, the scaling appears to vary with B^2 as expected from Eq. (8).

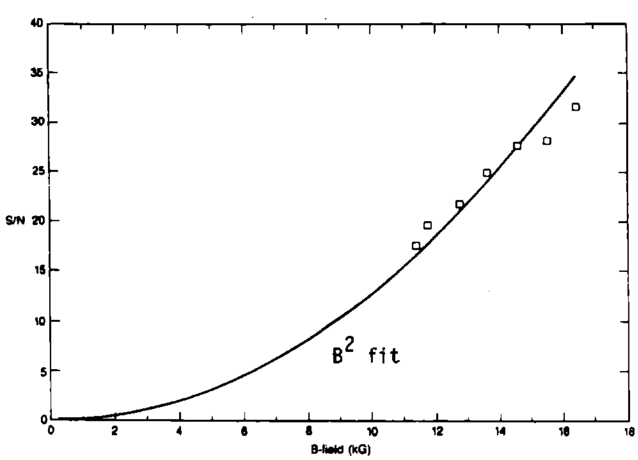

Figure 9. S/N vs $|B|$ with the probe impedance match retuned for each data point.

A final measurement of great interest in MFTF-B is the behavior of the NMR probe as a function of temperature. In MFTF-B, the NMR probes will be mounted directly to LN magnet liners. Without heating, the probe temperature is expected to approach the temperature of LN (-195°C). Figure 10 illustrates a NMR probe scan taken at 22.8 kG with the NMR sample at LN temperature. Note that the NMR decay following the pulses is clearly visible but that the spin-echo signal is no longer observed. This is probably due to the fact that the magnetic moment relaxation time has increased, and the sample can no longer return to an equilibrium state between pulse repetitions (~ 20 Hz). Due to the field gradients found in MFTF-B, we would like to make the field measurement using the spin-echo technique, so a 1 kΩ 1/4 W resistor has been placed in thermal contact with each probe to heat the sample. The heater current is dc and has no effect on the ac resonance signal. A small thermistor in parallel with the heating resistor gives an indication of the temperature.

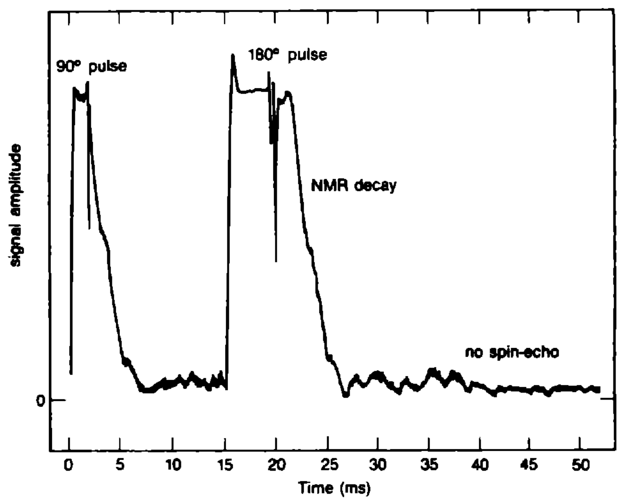

Figure 10. NMR probe trace with probe at LN_2 temperature -195°C (B = 28.8 kG, ∇B = 0).

Conclusion

A set of NMR probes has been designed to measure the magnetic field profile in MFTF-B by taking advantage of the phenomenon known as spin-echo. Prototype tests have shown that the NMR probes will satisfy the requirements for a one-time field profile measurement during the magnet acceptance tests. The scaling of S/N with various field and probe parameters has been measured and is in agreement with simple design formulas presented. Using standard laboratory equipment, the techniques presented here can easily be applied to accurately measure magnetic field magnitudes in a large variety of fusion and laboratory magnet systems.

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